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Patentanmeldung Nr. | Patent application No. | Demande de brevet n°

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Der Präsident des Europäischen Patentamts;
Im Auftrag

For the President of the European Patent Office

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INTERFERENTIAL DISPLACEMENT MEASURING SYSTEM FOR LITHOGRAPHIC PROJECTION APPARATUS

The present invention relates to interferential displacement measuring systems for use in lithographic projection apparatus comprising:

an illumination system for supplying a projection beam of radiation;

a first object table for holding a mask;

a second object table for holding a substrate; and

a projection system for imaging an irradiated portion of said mask onto a target portion of said substrate.

For the sake of simplicity, the projection system may hereinafter be referred to as the "lens"; however, this term should be broadly interpreted as encompassing various types of projection system, including refractive optics, reflective optics, and catadioptric systems, for example. The illumination system may also include elements operating according to any of these principles for directing, shaping or controlling the projection beam, and such elements may also be referred to below, collectively or singularly, as a "lens". In addition, the first and second object tables may be referred to as the "mask table" and the "substrate table", respectively.

Lithographic projection apparatus can be used, for example, in the manufacture of integrated circuits (ICs). In such a case, the mask (reticle) may contain a circuit pattern corresponding to an individual layer of the IC, and this pattern can be imaged onto a target area (comprising one or more dies) of a substrate (silicon wafer) which has been coated with a layer of radiation-sensitive material (resist). In general, a single wafer will contain a whole network of adjacent target areas which are successively irradiated via the reticle, one at a time. In one type of lithographic projection apparatus, each target area is irradiated by exposing the entire mask pattern onto the target area in one go; such an apparatus is

commonly referred to as a wafer stepper. In an alternative apparatus — which is commonly referred to as a step-and-scan apparatus — each target area is irradiated by progressively scanning the mask pattern under the projection beam in a given reference direction (the "scanning" direction) while synchronously scanning the substrate table parallel or anti-parallel to this direction; since, in general, the projection system will have a magnification factor M (generally < 1), the speed V at which the substrate table is scanned will be a factor M times that at which the mask table is scanned. More information with regard to lithographic devices as here described can be gleaned from International Patent Application WO97/33205, for example.

In general, lithographic apparatus contain a single mask table and a single substrate table. However, machines are becoming available in which there are at least two independently movable substrate tables; see, for example, the multi-stage apparatus described in International Patent Applications WO98/28665 and WO98/40791. The basic operating principle behind such multi-stage apparatus is that, while a first substrate table is at the exposure position underneath the projection system for exposure of a first substrate located on that table, a second substrate table can run to a loading position, discharge a previously exposed substrate, pick up a new substrate, perform some initial measurements on the new substrate and then stand ready to transfer the new substrate to the exposure position underneath the projection system as soon as exposure of the first substrate is completed; the cycle then repeats. In this manner it is possible to increase substantially the machine throughput, which in turn improves the cost of ownership of the machine. It should be understood that the same principle could be used with just one substrate table which is moved between exposure and measurement positions.

One of the most challenging requirements for micro-lithography for the production of integrated circuits as well as liquid crystal display panels is the positioning of tables. For example, sub-100 nm lithography demands substrate- and mask-positioning stages with dynamic accuracy and matching between machines to the order of 1 nm in all 6 degrees of freedom (DOF), at velocities of up to 2 ms^{-1}.

A popular approach to such demanding positioning requirements is to sub-divide the stage positioning architecture into a coarse positioning module (e.g. an X-Y table or a gantry table) with micrometer accuracies but travelling over the entire working range, onto which is cascaded a fine positioning module. The latter is responsible for correcting for the residual error of the coarse positioning module to the last few nanometers, but only needs to accommodate a very limited range of travel. Commonly used actuators for such nano-positioning include piezoelectric actuators or voice-coil type electromagnetic actuators. While positioning in the fine module is usually effected in all 6 DOF, large-range motions are rarely required for more than 2 DOF, thus easing the design of the coarse module considerably.

The micrometer accuracy required for the coarse positioning can be readily achieved using relatively simple position sensors, such as optical or magnetic incremental encoders. These can be single-axis devices with measurement in one DOF, or more recently multiple (up to 3) DOF such as those described by Schäffel et al "Integrated electro-dynamic multi-coordinate drives", Proc. ASPE Annual Meeting, California, USA, 1996, p.456-461. Similar encoders are also available commercially, e.g. position measurement system Type PP281R manufactured by Dr. J. Heidenhain GmbH. Although such sensors can provide sub-micrometer level resolution without difficulty, absolute accuracy and in particular thermal stability over long travel ranges are not readily achievable.

Position measurement for the mask / substrate table at the end of the fine positioning module, on the other hand, has to be performed in all 6 DOF to sub-nanometer resolution, with nanometer accuracy and stability over the entire working range. This is commonly achieved using multi-axis interferometers to measure displacements in all 6 DOF, with redundant axes for additional calibration functions (e.g. calibrations of interferometer mirror flatness on the substrate table).

Although the technology behind such interferometer systems is very mature, their application is not without problems. One of the most significant drawbacks of the interferometer is the dependence of wavelength on environmental pressure and

temperature, as described by Schellekens P.H.J. "Absolute measurement accuracy of technical laser interferometers" Ph.D. Thesis, TU Eindhoven, 1986, which is given by:

$$\lambda_a = \frac{\lambda_v}{\eta} \tag{1}$$

where:

$$(\eta - 1)_{P,T,H,C} = \frac{D \times 0.104126 \times 10^{-4}.P}{1 + 0.3671 \times 10^{-2}.T} - 0.42066 \times 10^{-9}.H \tag{2}$$

$$D = 0.27651754 \times 10^{-3} \times \left[1 + 53.5 \times 10^{-8}(C - 300)\right]$$

P:	atmospheric pressure [Pa]
T:	atmospheric temperature [°C]
H	water vapor pressure [Pa]
C	CO_2 content [ppm]

This remains one of the major problems in the thermal design of an optical lithography system. Typically, both temperature and pressure along the optical path of the interferometer has to be actively controlled to mK and mbar levels by the use of dry, clean (to better than Class 1) air, e.g. supplied by air showers.

In addition, the mounting adjustment of multi-axis interferometers for orthogonality and coplanarity, as well as the subsequent calibration procedure to remove any residual errors, are both extremely complex and time consuming. Even after such adjustments and calibration procedures, the measurement is only accurate if the relative positions of the interferometer blocks remain stable. The nanometer dimensional stability requirements of the metrology frame, on which the interferometer blocks are mounted, imply that the metrology frame has either to be made out of a material with low or zero coefficient of thermal expansion (CTE), such as Invar or Zerodur, or active thermal stabilization to mK levels, or both. Furthermore, the pointing stability of the laser beam during operation may introduce additional cosine or Abbe errors which need to be calibrated out on a regular basis by some form of automated routine.

An interferometer system is of course only a relative measuring system, capable of measuring changes in length (of optical path, to be more precise). Zero reference in each

degree of freedom can only be generated with additional equipment, such as so-called alignment sensors as described in WO 98/39689.

Although metrology frames in state-of-the-art lithography systems are highly isolated from ambient vibration, thermal deformation of the order of 0.5×10^{-9}m is not totally avoidable. It is, therefore, desirable that the position of the substrate or mask tables be measured directly relative to the optical imaging system. Mounting of interferometers directly on the lens, for example, is both difficult and undesirable. Relative length measurement to the lens can, however, still be realized by differential interferometry, at the expense of the added complication and cost.

The multiple beams required for such 6 DOF interferometric measurement cannot be adequately supplied with sufficient optical power by one laser source, thus requiring multiple sources with additional wavelength matching demands. The total thermal dissipation of the lasers and detectors combined exceeds 50W, which is well above the level allowable for the dimensional stability of the metrology frame. Both the lasers and the detectors have thus to be mounted remotely via optical links.

As can be seen, whilst the resulting interferometry based system is technically viable and has been implemented in practice, it is by no means simple, robust and economical.

The most obvious alternative to interferometers for long-range displacement measurements with micrometer or nanometer resolutions is the optical incremental encoder. Optical encoders with sub-nanometer resolutions have become available in recent years and have been promoted as viable alternatives to single-axis interferometry. The sub-nanometer resolution is achieved by using fine-pitched gratings (down to 512 nm) in combination with interpolation techniques (up to 4096 x). Most of such encoders, however, provide length measurement in 1 DOF only. As such, they do not lend themselves readily to nano-metrology in all 6 DOF simultaneously. Amongst the difficulties is the high level of crosstalk of the displacement signal to parasitic movements in the other 5 DOF.

It is an object of the invention to provide an improved displacement measuring system for use in a lithographic projection apparatus, and especially a system in which problems suffered by existing systems are solved or ameliorated.

According to the invention there is provided a lithographic projection apparatus comprising:

an illumination system for supplying a projection beam of radiation;

a first object table for holding a mask;

a second object table for holding a substrate; and

a projection system for imaging an irradiated portion of said mask onto a target portion of said substrate; characterized by:

displacement measuring system for measuring the position of one of said object tables in at least two degrees of freedom, said displacement measuring system comprising at least one grid grating mounted on said one object table and at least one sensor head for measuring displacements of said grid grating in two degrees of freedom.

A major advantage of the 2D grid encoder is that the measurement grid can be permanently fixed on a grating plate. Even if the grating is not perfectly orthogonal, straight or linear, this remains unchanged as long as the grating plate is free from distortions (either thermal or elastic). Such linearity or orthogonality errors can be calibrated out without too much difficulty by, for example, vacuum interferometry. The calibration only needs to be performed once for each grating, or not at all if one is only interested in positional repeatability. The use of a grid encoder essentially removes the guideway straightness and orthogonality from the error budget, when compared with single-axis encoder-based solutions.

The present invention can therefore provide an alternative solution to interferometry, at least in 3 coplanar degrees of freedom (X, Y, Rz), by combining the principles of grid gratings and sub-nanometer encoding.

To address the issue of output sensitivity to parasitic movements in the remaining degrees of freedom of encoders with nanometer resolutions, systems used in the present invention make use of the interference pattern of the first order diffraction of the collimated incidence light from a monochromatic source off the grating. This method ensures that the signals at the detector are free from high-order harmonics, making it possible to perform very high interpolation without incurring excessive errors. In addition, it allows a much larger position latitude of the reading head relative to the grating in the non-measurement directions.

A typical system used in the present invention comprises a grid grating with a period of 10 μm or less, with an interferential reading (encoder) head in 2 DOF and an interpolator of up to a factor of 20,000 for each axis.

For the measurement of the remaining 3 DOF, namely Z, Rx and Ry, various short range displacement sensing technologies can be employed, including optical triangulation, fiber-optic back-scatter, interferometric sensors (which can have a very short optical path in air and therefore be much less sensitive to environmental fluctuations), capacitive or inductive sensors.

Currently, capacitive and optical sensors are preferred to the other measuring principles, though the others may be appropriate in some applications of the invention. The use of inductive sensors against a Zerodur chuck is problematic, as conductive targets are required for the sensors. Pneumatic proximity sensors (air micrometer), on the other hand, suffer from limited resolution and working distance, as well as exerting a finite force on the target.

Optical sensors, whether interferometric or triangulated, can be designed with a relatively large (a few millimeters) working distance, which helps to ease assembly tolerances. Compared to capacitive sensors, they usually have higher bandwidths, and can be configured as an absolute distance sensor. As an absolute sensor, however, they do suffer from long-term stability problems due to mechanical drifts (thermal or otherwise) requiring periodic calibration.

Capacitive sensors, on the other hand, can be designed as an absolute sensor with very high stability. Furthermore, the distance measurement is performed over a relatively large target surface, which helps to reduce any effects of localized unevenness of the target surface. Despite their limited measurement range and stand-off clearance, they are currently the preferred choice in lithographic applications.

An encoder based nano-positioning system offers an advantageous alternative to interferometry and is much simpler to implement. Better measurement stability can be achieved by the fact that the measurement grid in the X-Y plane is permanently fixed onto the mask table, which when implemented in a zero-CTE material, such as Zerodur, is both long-term dimensionally stable and thermally insensitive. This eases considerably the stringent demand on environmental control of the area immediately around the optical path of the interferometer beams, particularly in the case of a lithographic projection apparatus employing wavelengths of 157 nm or below. Such devices require to be purged with gas, that does not absorb the beam (which is strongly absorbed in air) and by avoiding the need for air showers over the length of the interferometer beams, the present invention can substantially reduce consumption of purge gas.

The mask position relative to the projection optics can also be measured in the encoder solution without resorting to a differential configuration. Although placing the reading head directly on the top of the projection optics does put more demands on the thermal dissipation of the former, techniques to minimize this such as active cooling or remote light source and detectors linked by optical fibers are already available and already deployed in state-of-the-art interferometer systems.

The invention also provides a method of manufacturing a device using a lithographic projection apparatus comprising:

an illumination system for supplying a projection beam of radiation;

a first object table for holding a mask;

a second object table for holding a substrate; and

a projection system for imaging irradiated portions of said mask onto target portions of said substrate; the method comprising the steps of:

providing a mask bearing a pattern to said first object table;

providing a substrate provided with a radiation-sensitive layer to said second object table;

using said interferometric displacement measuring means to measure the position of said movable object table;

irradiating portions of the mask and imaging said irradiated portions of the mask onto said target portions of said substrate; characterized by the step of:

measuring displacements of one of said object tables in at least two degrees of freedom using at least one grid grating mounted thereon and at least one sensor head.

In a manufacturing process using a lithographic projection apparatus according to the invention, a pattern in a mask is imaged onto a substrate which is at least partially covered by a layer of radiation-sensitive material (resist). Prior to this imaging step, the substrate may undergo various procedures, such as priming, resist coating and a soft bake. After exposure, the substrate may be subjected to other procedures, such as a post-exposure bake (PEB), development, a hard bake and measurement/inspection of the imaged features. This array of procedures is used as a basis to pattern an individual layer of a device, e.g. an IC. Such a patterned layer may then undergo various processes such as etching, ion-implantation (doping), metallization, oxidation, chemo-mechanical polishing, etc., all intended to finish off an individual layer. If several layers are required, then the whole procedure, or a variant thereof, will have to be repeated for each new layer. Eventually, an array of devices (dies) will be present on the substrate (wafer). These devices are then separated from one another by a technique such as dicing or sawing, whence the individual devices can be mounted on a carrier, connected to pins, etc. Further information regarding such processes can be obtained, for example, from the book "Microchip Fabrication: A Practical Guide to Semiconductor Processing", Third Edition, by Peter van Zant, McGraw Hill Publishing Co., 1997, ISBN 0-07-067250-4.

Although specific reference may be made in this text to the use of the apparatus according to the invention in the manufacture of ICs, it should be explicitly understood that such an apparatus has many other possible applications. For example, it may be

employed in the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, liquid-crystal display panels, thin-film magnetic heads, etc. The skilled artisan will appreciate that, in the context of such alternative applications, any use of the terms "reticle", "wafer" or "die" in this text should be considered as being replaced by the more general terms "mask", "substrate" and "exposure area" or "target area", respectively.

The invention is described below with reference to a coordinate system based on orthogonal X, Y and Z directions with rotation about an axis parallel to the I direction denoted Ri. The Z direction may be referred to as "vertical" and the X and Y directions as "horizontal". However, unless the context otherwise demands, this should not be taken as requiring a specific orientation of the apparatus.

The invention and its attendant advantages will be further described below with reference to exemplary embodiments and the accompanying schematic drawings, in which:

Figure 1 depicts a lithographic projection apparatus according to a first embodiment of the invention;

Figure 2 is a perspective view of the mask stage of a known lithographic apparatus, showing the position measuring system;

Figure 3 is a perspective view of the mask stage of a lithographic apparatus, showing the position measuring system according to a first embodiment of the invention; and

Figures 4 and 5 are graphs showing measurements taken in a calibration procedure according to the present invention.

In the drawings, like parts are identified by like references.

Embodiment 1

Figure 1 schematically depicts a lithographic projection apparatus according to the invention. The apparatus comprises:

- a radiation system comprising radiation source LA, and illumination system IL (Ex, IN, CO) for supplying a projection beam PB of radiation (e.g. UV or EUV radiation);
- a first object table (mask table) MT for holding a mask MA (e.g. a reticle), and connected to first positioning means for accurately positioning the mask with respect to item PL;
- a second object table (substrate or wafer table) WT for holding a substrate W (e.g. a resist-coated silicon wafer), and connected to second positioning means for accurately positioning the substrate with respect to item PL;
- a projection system ("lens") PL (e.g. a refractive or catadioptric system or a mirror group) for imaging an irradiated portion of the mask MA onto an exposure area C (target portion) of a substrate W held in the substrate table WT.

As here depicted, the apparatus is of a transmissive type (i.e. has a transmissive mask). However, in general, it may also be of a reflective type, for example.

The radiation system includes a source LA (e.g. an Hg lamp, an excimer laser, an undulator or wiggler provided around the path of an electron beam in a storage ring or synchrotron or a plasma source) which produces a beam of UV or EUV radiation. This beam is caused to traverse various optical components comprised in the illumination system IL — e.g. beam shaping optics Ex, an integrator IN and a condenser CO — so that the resultant beam PB has a desired shape and intensity distribution in its cross-section. The beam PB subsequently intercepts the mask MA which is held on a mask table MT. Having passed through the mask MA, the beam PB passes through the lens PL, which focuses the beam PB onto an exposure area C of the substrate W. With the aid of the displacement measuring means DM, the substrate table WT can be moved accurately by the second positioning means, e.g. so as to position different exposure areas C in the path of the beam PB. Similarly, the first positioning means can be used with the aid of second displacement measuring means (not shown) to accurately position the mask MA with respect to the path of the beam PB. In general, movement of the object tables MT, WT will be realized with the aid of a long-stroke module (course positioning) and a short-stroke module (fine positioning), which are not explicitly depicted in Figure 1. In the case of a

waferstepper (as opposed to a step-and-scan apparatus) the reticle table may be connected only to a short-stroke positioning device, to make fine adjustments in mask orientation and position, or may be fixed. Most components of the apparatus, including all vibration generating components, are mounted on or from the base plate BP and base frame BF. However, the projection lens, as well as necessary components of the interferometric displacement measuring means and other sensors are mounted on the reference, or metrology, frame RF which is mechanically isolated from the rest of the apparatus to provide a stable reference.

The depicted apparatus can be used in two different modes:

1. In step-and-repeat (step) mode, the mask table MT is kept essentially stationary, and an entire mask image is projected in one go (i.e. a single "flash") onto an exposure area C. The substrate table WT is then shifted in the X and/or Y directions so that a different exposure area C can be irradiated by the beam PB;

2. In step-and-scan (scan) mode, essentially the same scenario applies, except that a given exposure area C is not exposed in a single "flash". Instead, the mask table MT is movable in a given reference direction (the so-called "scan direction", e.g. the Y direction) with a speed v, so that the projection beam PB is caused to scan over a mask image; concurrently, the substrate table WT is moved in the same or opposite direction at a speed $V = Mv$, in which M is the magnification of the lens PL (typically, $M = 1/4$ or $1/5$). In this manner, a relatively large exposure area C can be exposed, without having to compromise on resolution.

According to the first embodiment of the invention, the displacement measuring means for the mask table comprises a 6 DOF, non-interferometric, nano-metrology system which comprises a table made of Zerodur, on the underside of which are exposed two grid gratings. Each of these gratings, one on either side of the table along the Y-direction, has a measurement range of, for example, 10 mm x 500 mm. Two two-coordinate reading heads, mounted on either side of the lens top, measure displacements of the mask table in X, Y, Rz with respect to the lens, with redundant information for X. The two-dimensional gratings are dimensionally stable to nanometer levels over a reasonable temperature range

due to the near-zero coefficient of thermal expansion (CCTE) of Zerodur, thus offering a 'permanent' frame of dimensional reference. To minimize any Abbe error due to pitch and roll, the grating should preferably be coplanar to the patterned surface of the mask. Additional indexing channels in X, Y_1 and Y_2 can also be implemented to provide zero references relative to the lens.

Displacements in the other 3 degrees of freedom (Z, Rx, Ry) can be measured by means of a minimum of 3 nano-height gauges. For the particular case of a transmissive mask, the center portions of the lens and the mask table have to be kept clear. As such, a four-sensor layout is more convenient for implementation.

Similar to displacement in the X-Y plane, it is more convenient to have the sensing target (reflective surface for an optical sensor, or electrode for a capacitive sensor) on the Zerodur table, and the active part of the sensor on the lens top. This avoids, amongst others, having to route sensor cables to the nano-positioned mask table. The height gauges can use the 2D-grating as their targets, or separate targets can be provided on the Zerodur table.

In contrast with the case of interferometers, the actual mounting positions and orthogonalities of the sensor heads as well as the target surfaces are less critical as long as they remain stable, as they can be determined by a calibration procedure on the lithographic machine. As already mentioned, while laser interferometer is unrivalled in terms of accuracy, the incremental encoder is superior in terms of repeatability due to the sensitivity of the former to environmental conditions.

Gratings for use in the present invention are preferably manufactured using a laser interferometer in a highly controlled environment (e.g. vacuum) to make a master encoder grating with the highest possible accuracy. Then production gratings are replicated from the master — taking advantage of the encoder's inherently high repeatability. The replicas can further be calibrated, either against the master grating or against a vacuum interferometer.

A crucial factor in the practicability of calibration is the spatial frequency content of the errors. An encoder with high spatial-frequency errors will require a high density of

calibration data, as well as a high-accuracy reference mark to initialize the application of corrections to measured position data.

Before describing a displacement measurement system according to the present invention, a conventional system will be outlined with reference to Figure 2 to emphasize the advantages of the present invention.

In the conventional system, the mask table MT has a relatively long range of movement in the Y-direction to accommodate the scan of the mask during the imaging process. Throughout this large-range motion, the Y position of the mask table MT is measured using two Y1-IF, Y2-IF which direct measurement beams against one or more mirrors or reflectors mounted on the mask table MT. The measurement beams are incident on the mask table as two spaced-apart points so that the difference between the two resulting readings can be used to determine the Rz position of the mask table. At at least one extreme of the range of motion of the mask table, the measurement beams will extend over a considerable distance and any variation in the refractive index of the atmosphere through which they pass can therefore introduce a significant error into the position measurements. The X position of the mask table is measured by X-interferometer X-IF. Although the range of motion of the mask table in the X-direction is considerably smaller than that in the Y-direction, so the optical path length of the X-interferometer does not need to be so long, the X-interferometer must provide a measurement of X position throughout the range of motion of the mask table in the Y-direction. This requires that the measurement beam of the X-interferometer X-IF must be directed onto a mirror mounted on the side of the mask table MT and having a length greater than the scanning range of the mask table MT.

In the conventional system, the three interferometers provide measurements of displacements of the mask table in three degrees of freedom, namely X, Y and Rz (yaw). The position in the other three degrees of freedom, i.e. Z, Rx (pitch) and Ry (roll), is provided by appropriate processing of the outputs from three height sensors HS which measure the vertical position of three points spaced apart on the bottom of the mask table MT.

By way of comparison, the arrangement according to the first embodiment of the present invention is shown in Figure 3. In place of the interferometers Y1-IF, Y2-IF and X-IF, the present invention employs two optical reading heads 10, 11 which measure displacements of respective grid gratings 12, 13. The grid gratings 12, 13 are provided one on either side of the mask MA and have a length in the Y-direction sufficient to accommodate the entire scanning range of motion, indicated by the double-headed arrow, of the mask table MT. The grid gratings 12, 13 are positioned on cut-away portions so that they are substantially co-planar with a pattern on the mask MA. The encoder reading heads 10, 11 as well as three height sensors HS are mounted on, or fixed relative to, the upper element of the projection system, represented by the dashed oval in Figure 3.

The encoder reading heads 10, 11 can be actively temperature-controlled, e.g. by incorporating a water-cooling jacket, to remove any heat dissipated by them and maintain thermal stability of the reading head itself and the projection optics to which they are mounted. Also, the light source and the detectors of the reading head can be located remotely and coupled to the reading head via optical fibres, so as to minimize any local heat generation and maintain the highest possible pointing stability in the reading head optics.

As can be seen from Figures 2 and 3, the encoder measurement system is much more compact, and removes the need for extending the metrology reference frame from the wafer level to the reticle level, the two being some 1m apart in the vertical direction. The resultant design of the metrology frame is much simpler and more compact, with substantial improvements in its dynamic characteristics. The concept can be taken further to measure the X-Y position of the mask itself relative to the projection optics. This can be done by putting a reflective grating directly on the chrome border around the pattern area of the mask. While this increases the costs of the mask, any distortions in the plane of the mask due to e.g. dimensional changes during processing can be automatically accounted for. The availability of a reference index position in X, Y and Rz is yet an additional bonus.

In order to determine the accuracy of an X-Y encoder and calibrate it for use in the invention, the following procedure can be used:

1. Mount the encoder on an X-Y stage equipped with a laser interferometer on at least one axis. Adjust its orientation so that the encoder axes are parallel with the stage axes (while moving the stage in X adjust the encoder orientation so that measured motion in the Y direction is minimized).

2. Move the stage at a constant low velocity in the X direction; minimize air turbulence and collect simultaneous data (at a clocked rate) from both the laser interferometer and the encoder readout sensor.

3. Rotate the X-Y encoder by 90° and repeat data collection.

4. Plot the data in the form of Non-Linear Error vs. Position for both sets of data.

The plotted data will serve to clearly indicate the spatial frequency content of the encoder errors. Some averaging of the laser interferometer data may be effective in reducing the effects of any residual turbulence on the measurements. Repeated nominally identical measurement runs will give an indication of the effects of turbulence on repeatability.

Figure 4 shows a typical plot of the type described above. This plot was obtained by mounting an X-Y encoder on an X-Y stage equipped with a single-axis laser-interferometer, and recording data for two nominally identical scans. The differences between the two scans are due to varying turbulence along the air paths within the laser interferometer.

Raw position data from the interferometer and the encoder are processed by doing a linear regression of the data (Laser data = independent variable, Encoder Data = dependent variable) and then plotting the difference between the actual encoder data and the linear fit to the laser interferometer data. The slope of the linear fit is a correction factor to be applied to all of the encoder data, and represents an error in the mean pitch of the encoder.

The plot of Figure 4 provides a calibration of the X (or Y) encoder vs. the laser interferometer at a single Y (or X) position. The spatial frequency content of the plot will dictate how closely spaced the calibration runs should be in order to fully characterize the accuracy of the grid to within a specified accuracy.

A full calibration of the encoder would then consist of a series of linear calibration runs in both the X and Y directions, with the number of runs being dictated by the spatial frequency content of a typical run. For an encoder with high spatial frequency errors, runs might have to be made every 4mm; for an encoder whose errors have less high frequency content, the spacing between runs might be 20mm. The final calibration data would be a series of error plots in both directions as shown in Figure 5. This figure shows a series of calibration curves for X-displacements of the X-Y stage at a series of different Y-positions (each separated by 11.43mm in the Y direction). There is a similar series of calibration curves for the Y-direction, taken at different X-positions. The number of curves needed to adequately characterize the X-Y encoder depends on the spatial frequency content of a typical single plot and on the desired accuracy of data that is to be corrected using the calibration information. In this instance the uncorrected accuracy of each scan is better than or equal to ± 100nm, and successive scans, separated by 11.43mm, agree with one another to within about 50nm (the 3rd scan from the top appears anomalous, perhaps due to turbulence during scan). These data could be used to correct the grid accuracy to about ± 50nm. Further improvement in the calibration accuracy could be achieved by (a) reducing the separation between successive scans, and (b) replacing single scans by the average of several scans in order to reduce the effects of random turbulence effects in the laser interferometer measurements. Alternatively, the grid could be calibrated at a finite array of points with each reading being averaged for 1 to 10 seconds.

A stringent assessment of the orthogonality of the grating requires calibration of the encoder using an X-Y stage with a certified metrology system (such as a laser interferometer with an accurate L-shaped mirror). On the other hand, if the encoder has been produced using laser-controlled microlithography, then there is every reason to believe that the overall accuracy of the encoder, including orthogonality errors, is properly characterized by the linear calibration plots. For example, if the linear calibration plots show that the accuracy along any single 200mm long axis is ± 80nm or better, then it is likely that the orthogonality is good to an angle of (± 80nm/200mm) » ± 0.4 mrad.

Whilst we have described above specific embodiments of the invention it will be appreciated that the invention may be practiced otherwise than described. The description is not intended to limit the invention. In particular, whilst the described embodiment is a system for measuring the position of a mask table in a lithographic apparatus, it will be appreciated that the invention is equally applicable to substrate (wafer) tables and to multiple stage devices.

CLAIMS:

1. A lithographic projection apparatus comprising:

an illumination system for supplying a projection beam of radiation;

a first object table for holding a mask;

a second object table for holding a substrate; and

a projection system for imaging an irradiated portion of said mask onto a target portion of said substrate; characterized by:

displacement measuring system for measuring the position of one of said object tables in at least two degrees of freedom, said displacement measuring system comprising at least one grid grating mounted on said one object table and at least one sensor head for measuring diplacements of said grid grating in two degrees of freedom.

2. Apparatus according to claim 1 wherein said displacement measuring system comprises two grid gratings mounted on said object table at spaced apart locations and two sensor heads each for measuring displacements of a respective one of said grid gratings.

3. Apparatus according to claim 1 or 2 wherein said object table is moveable in a first direction for scan imaging and the or each said grid grating has a length in said first direction greater than or equal to the range of motion of said object table in said first direction.

4. Apparatus according to claim 1, 2 or 3 wherein the or each said grid grating is substantially coplanar with the functional surface of an object held in the object table.

5. Apparatus according to any one of the preceding claims wherein the or each said grid grating is incorporated directly into the main body of said object table.

6. Apparatus according to any one of the preceding claims wherein said displacement measuring system further comprises a memory for storing correction information representing differences between the or each grid grating and an ideal grid grating and a data processing means for correcting measurements output by the or each sensor head.

7. Apparatus according to any one of the preceding claims wherein said displacement measuring system comprises one or more capacitive or optical sensors for measuring the position of said object table in degrees of freedom not measured by the or each grid grating and encoder head.

8. Apparatus according to any one of the preceding claims wherein the or each grid grating includes a reference mark detectable by the respective sensor head for defining a reference position of said object table.

9. Apparatus according to any one of the preceding claims wherein the or each sensor head comprises an encoder head.

10. Apparatus according to any one of the preceding claims wherein said displacement measuring system further comprises an interpolator for interpolating the output of the or each sensor head.

11. A method of manufacturing a device using a lithographic projection apparatus comprising:

an illumination system for supplying a projection beam of radiation;

a first object table for holding a mask;

a second object table for holding a substrate; and

a projection system for imaging irradiated portions of said mask onto target portions of said substrate; the method comprising the steps of:

providing a mask bearing a pattern to said first object table;

providing a substrate provided with a radiation-sensitive layer to said second object table;

irradiating portions of the mask and imaging said irradiated portions of the mask onto said target portions of said substrate; characterized by the step of:

measuring displacements of one of said object tables in at least two degrees of freedom using at least one grid grating mounted thereon and at least one sensor head.

12. A device manufactured according to the method of claim 11.

ABSTRACT

INTERFERENTIAL DISPLACEMENT MEASURING SYSTEM FOR LITHOGRAPHIC PROJECTION APPARATUS

The X, Y and Rx positions of a mask stage are measured using two optical encoder-reading heads measuring displacements of respective grid gratings mounted on the mask stage. The grid gratings are preferably provided on cut-away portions of the mask table so as to be co-planar with the pattern on the mask itself. Measurements of the table position in the other degrees of freedom can be measured with capacitative or optical height sensors.

Fig. 3

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Fig. 1

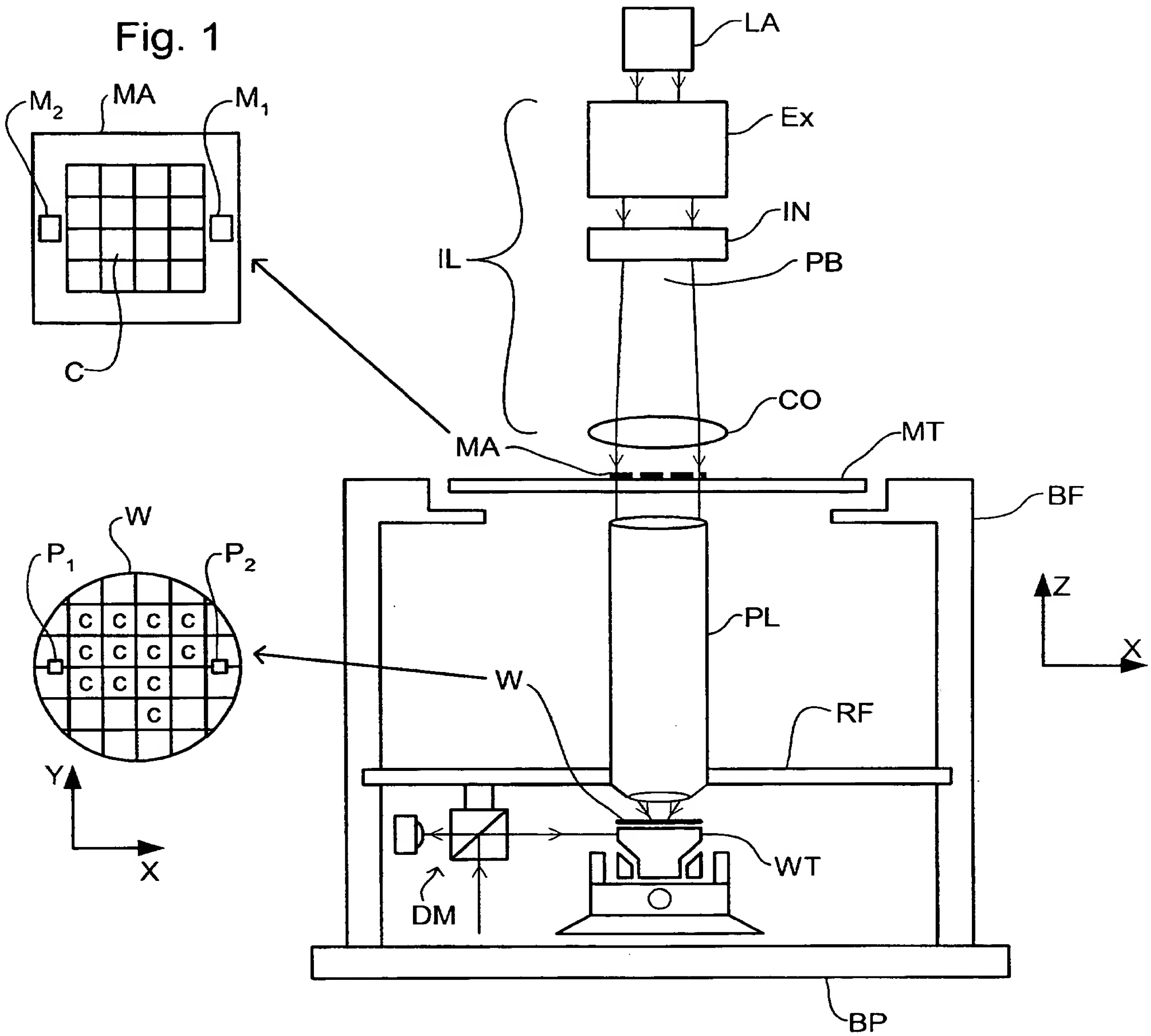


Fig. 2

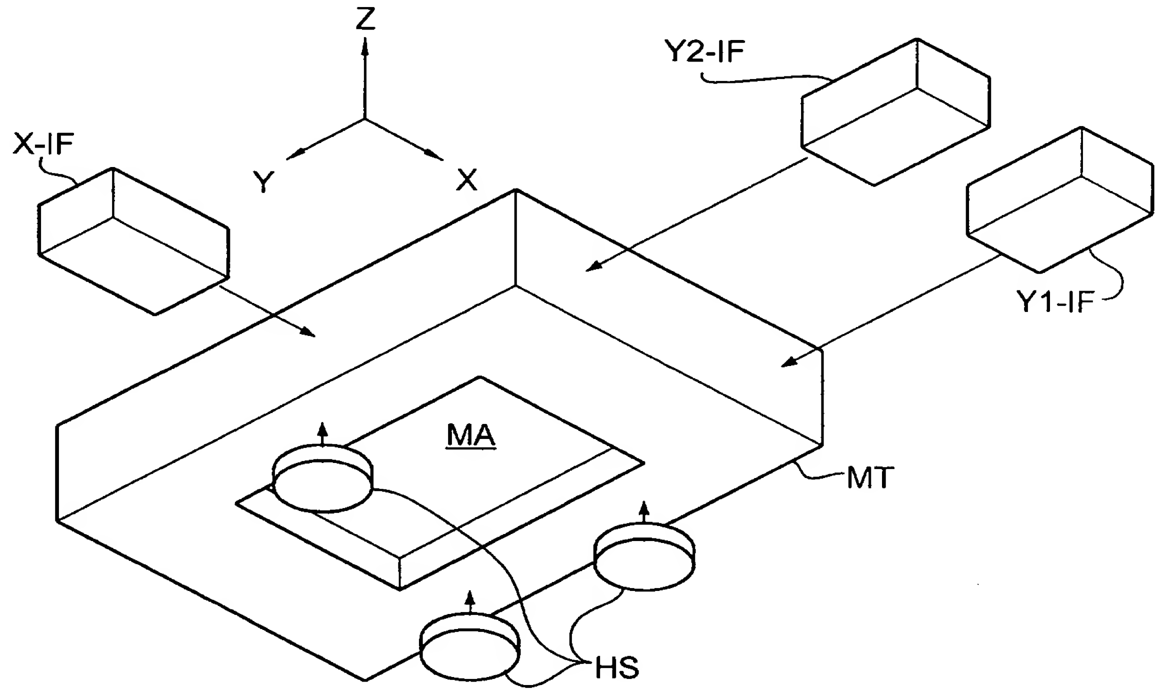


Fig. 3

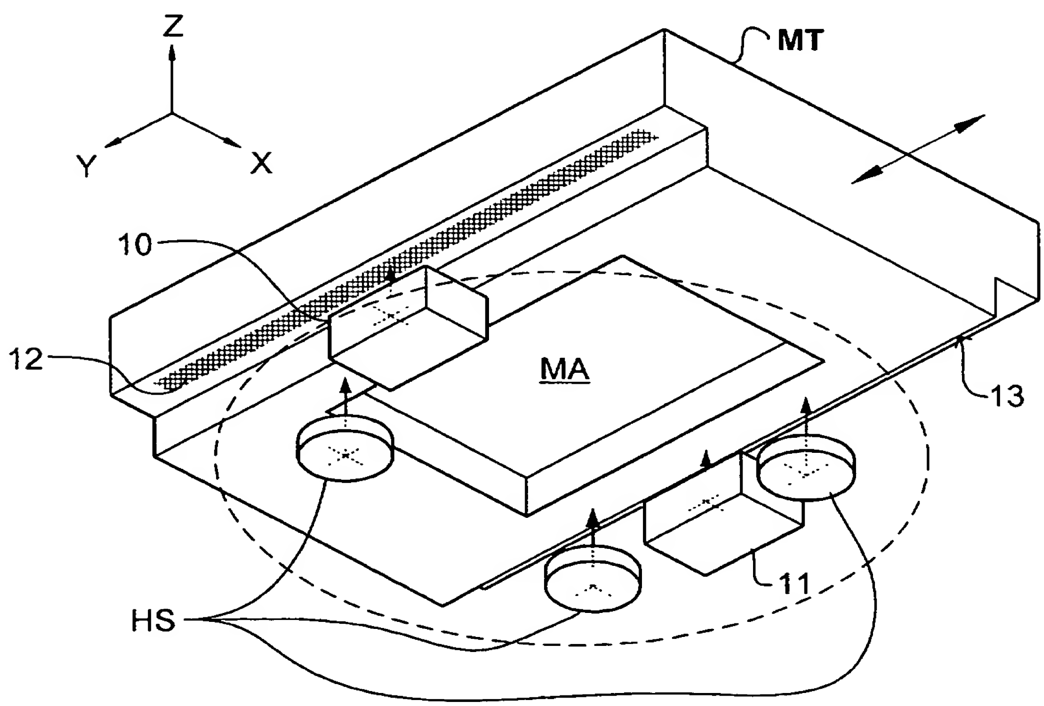


Fig. 4

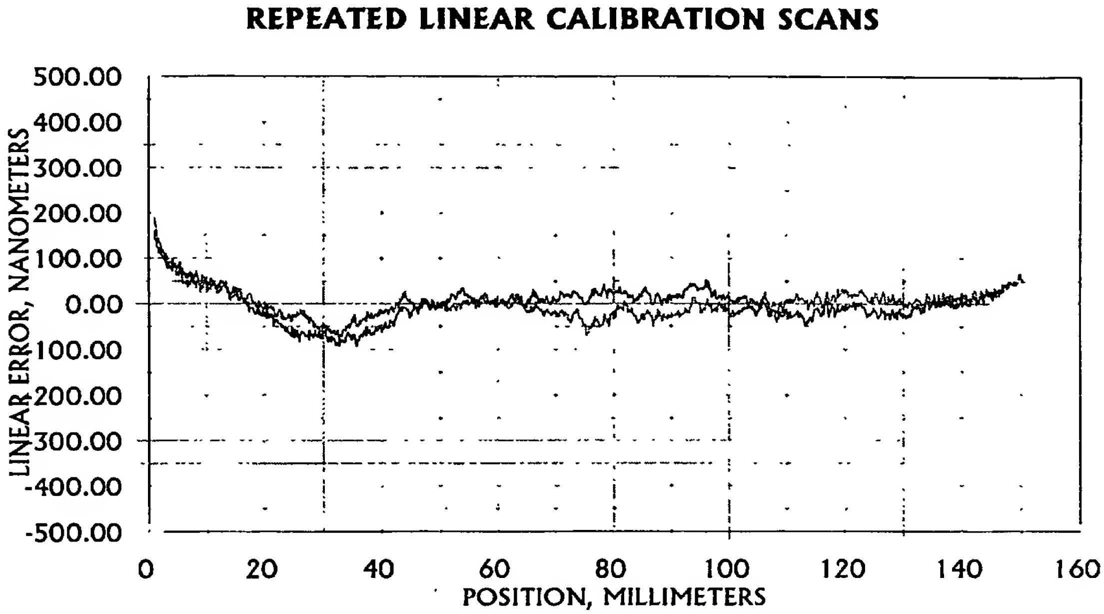
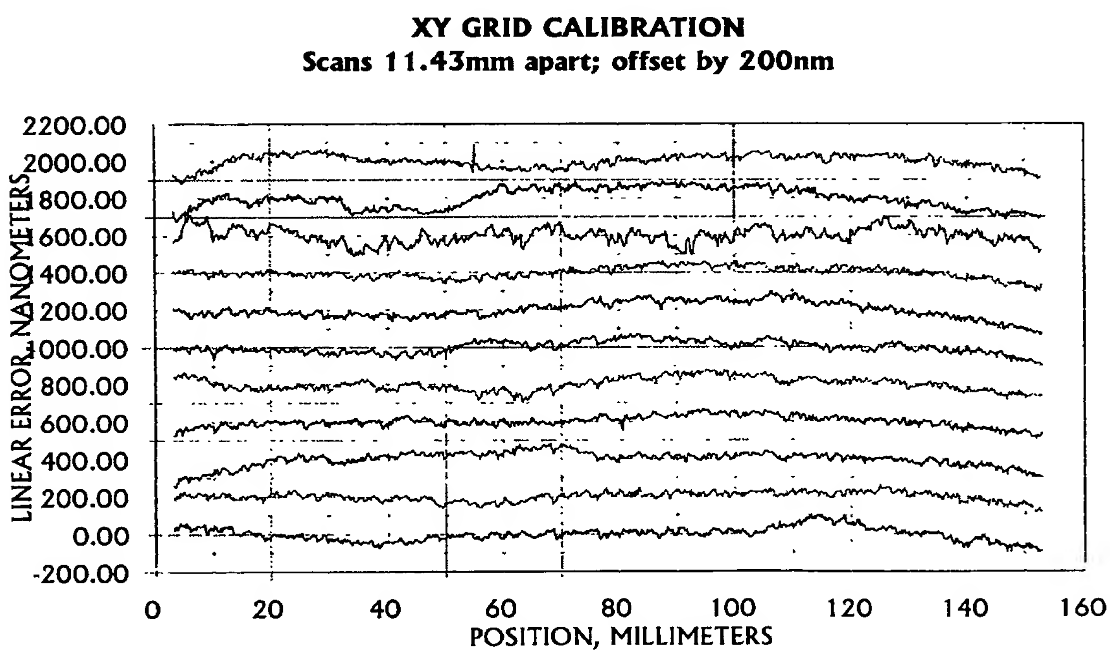

REPEATED LINEAR CALIBRATION SCANS
LINEAR ERROR, NANOMETERS
500.00
400.00
300.00
200.00
100.00
0.00
-100.00
-200.00
-300.00
-400.00
-500.00
0
20
40
60
80
100
120
140
160
POSITION, MILLIMETERS

Fig. 5


XY GRID CALIBRATION
Scans 11.43mm apart; offset by 200nm
LINEAR ERROR, NANOMETERS
2200.00
2000.00
1800.00
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
-200.00
0
20
40
60
80
100
120
140
160
POSITION, MILLIMETERS